X-ray measurement of residual stresses in laser surface melted Ti-6Al-4V alloy

Robinson, J.M.; van Brussel, B.A.; de Hosson, J.T.M.; Reed, R.C.

Published in:
Materials science and engineering a-Structural materials properties microstructure and processing

DOI:
10.1016/0921-5093(95)10158-6

Publication date:
1996

ELSEVIER

Materials Science and Engineering A208 (1996) 143–147

MATERIALS SCIENCE & ENGINEERING A

Letter

X-ray measurement of residual stresses in laser surface melted Ti-6Al-4V alloy

J.M. Robinson[a,1], B.A. Van Brussel[b], J. Th.M. De Hosson[b], R.C. Reed[a,1]

[a]Department of Materials, Imperial College of Science, Technology and Medicine, London SW7 2BP, UK
[b]Department of Applied Physics, Materials Science Centre, University of Groningen, Nijenborg 4, 9747 AG Groningen, The Netherlands

Received 29 September 1995

Abstract

In this paper, we report on the residual stresses in laser surface melted Ti-6Al-4V, determined using X-ray diffraction methods. The principal result is that there is an increase in the transverse residual stress with each successive, overlapping laser track. The result can be used to explain the observation of crack formation in overlapping tracks but not necessarily in single tracks produced under identical processing conditions.

Keywords: Titanium alloys; Laser surface melting; Residual stresses

1. Introduction

In general, titanium alloys exhibit a desirable combination of high specific strength and good corrosion resistance. However, engineering applications of the alloys are nonetheless restricted because of poor wear resistance. Surface engineering of titanium alloy components provides a means by which the desirable bulk properties may be retained in conjunction with enhanced wear resistance [1]. To this end, laser surface melting treatments represent a particularly attractive solution where relatively deep ($\geq$ 100 μm) protection is desirable [2]. The formation of a hard wear resistant layer is achieved by surface melting the metal in the presence of a reactive gas, usually nitrogen (e.g. [3,4]). In a single stage process therefore, a composite surface layer consisting of a substantial proportion of TiN embedded in a rapidly solidified matrix may be produced.

It is established that laser surface melting treatments generally result in predominantly tensile residual stresses within the processed layer e.g. [4,5]. In some cases, the severity of the stresses may be such that surface layer micro-cracking occurs. Indeed, such crack formation has frequently been observed to be specifically problematic in the case of laser nitrided titanium alloys e.g. [4,6]. Previously, it has been shown that the tendency for cracking in single laser tracks may be reduced by the dilution of the alloy gas with an inert carrier gas or by a combination of alloy-gas dilution and substrate pre-heating [4]. However, applications where controlled pre-heating may be employed are limited. It is therefore important to understand the detail of residual stress development associated with laser surface melting without pre-heating.

The production of a laser alloyed surface relies on the successive overlapping of adjacent laser tracks e.g. [6]. Single track studies have most recently been used to define process parameter regimes where micro-cracking does not occur [7]. However, in spite of the possibility of producing crack-free single tracks, critical additional information is required if the technique is to find viable application in the treatment of engineering components. First, it is imperative that the laser beam intensity profile is well characterised in order that the processing conditions may be readily repeated. Second, the effect of overlapping adjacent tracks on the residual stress distribution should be accurately understood. It is for these reasons that we have initiated the present work. Therefore we report here on the quantification of resid-

[1]Present address: University of Cambridge, Department of Materials Science and Metallurgy, Pembroke Street, Cambridge CB2 3QZ, UK

0921-5093/96/$15.00
SSDI 0921-5093(95)10158-9

Table 1
Chemical composition limits for the commercial alloy Ti-6Al-4V

Designation	Alloy	Al	V	N	C	H	Fe	O
IMI 318	Ti-6Al-4V	5.50 6.75	3.50 4.50	0.05	0.10	0.15	0.40	0.20

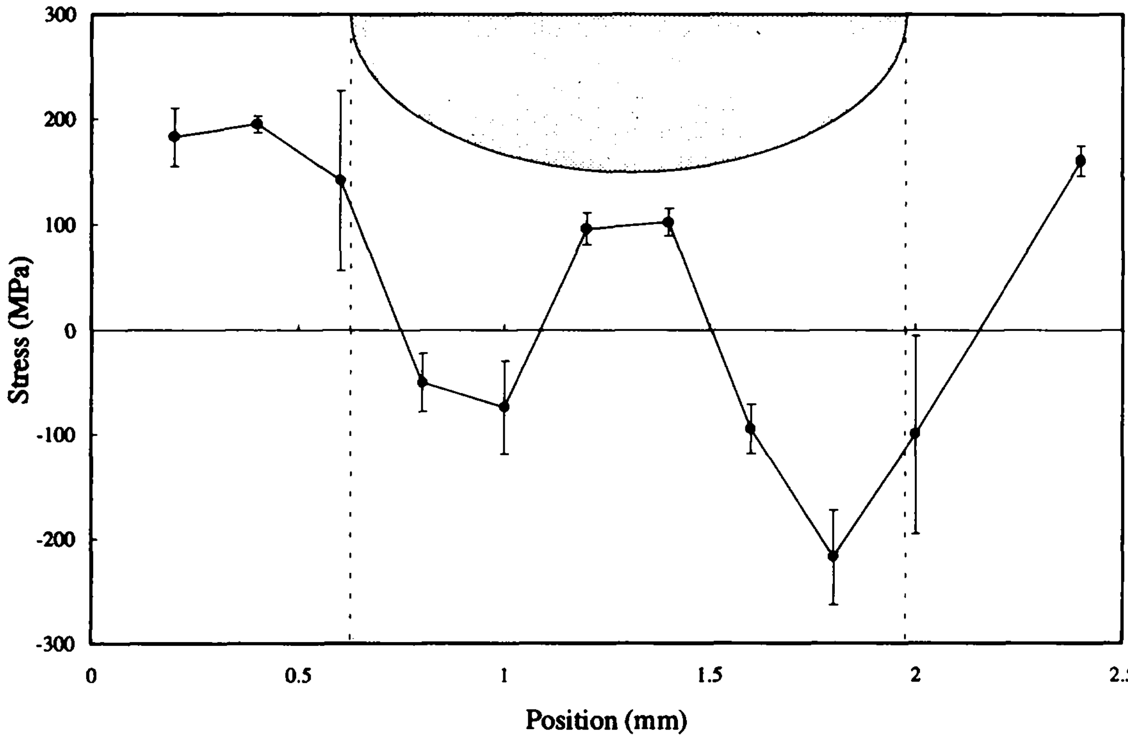


Fig. 1. The distribution of residual stress within a single laser melt track on Ti-6Al-4V substrate. The melt track cross-section is illustrated schematically within the figure.

ual stress within a single laser melt track on a Ti-6Al-4V substrate and subsequently examine the effect of multiple overlapping adjacent tracks.

2. Experimental technique

2.1. Material

The dual phase ($\alpha-\beta$) titanium alloy Ti-6Al-4V conforming to composition specifications detailed in Table 1 was used in the hot-rolled and annealed condition. Specimens were gritblasted, in order to improve the absorption of laser radiation and then ultrasonically cleaned in ethanol prior to laser treatment.

2.2. Laser treatment

Laser surface melting utilised a continuous wave, fast axial flow 1kW CO_2 (Ferranti MFK) laser. The TEM_{00} (Gaussian) mode beam was characterised using a hollow-needle beam analyser [8] and the power measured at the workpiece to within 5% using a calibrated calorimeter. All laser melt tracks were produced with a defocused beam of pre-determined radius ($r_{1/e} = 300$ μm) at a measured power of 950 W. To prevent atmospheric contamination of the melt pool, argon gas shrouding was supplied coaxial to the beam at a flow rate of 20 l min^{-1} through a 2 mm diameter nozzle. Nitrogen alloying of the melt pool was achieved by the controlled introduction of N_2 gas, measured by volume into the shroud gas.

The top width of the melt-pool was determined by transverse sectioning, polishing and etching the laser track using conventional metallographic techniques. Overlapping melt tracks were then produced by traversing the specimen by 0.75 mm between successive laser passes. This corresponds to an overlap of approximately 50% of the melt top width. The sample was allowed to cool below 50 °C between each successive pass in order to eliminate preheating effects.

Dye penetrant examination of samples was undertaken after laser melting in order to identify the process parameters associated with surface layer crack formation.

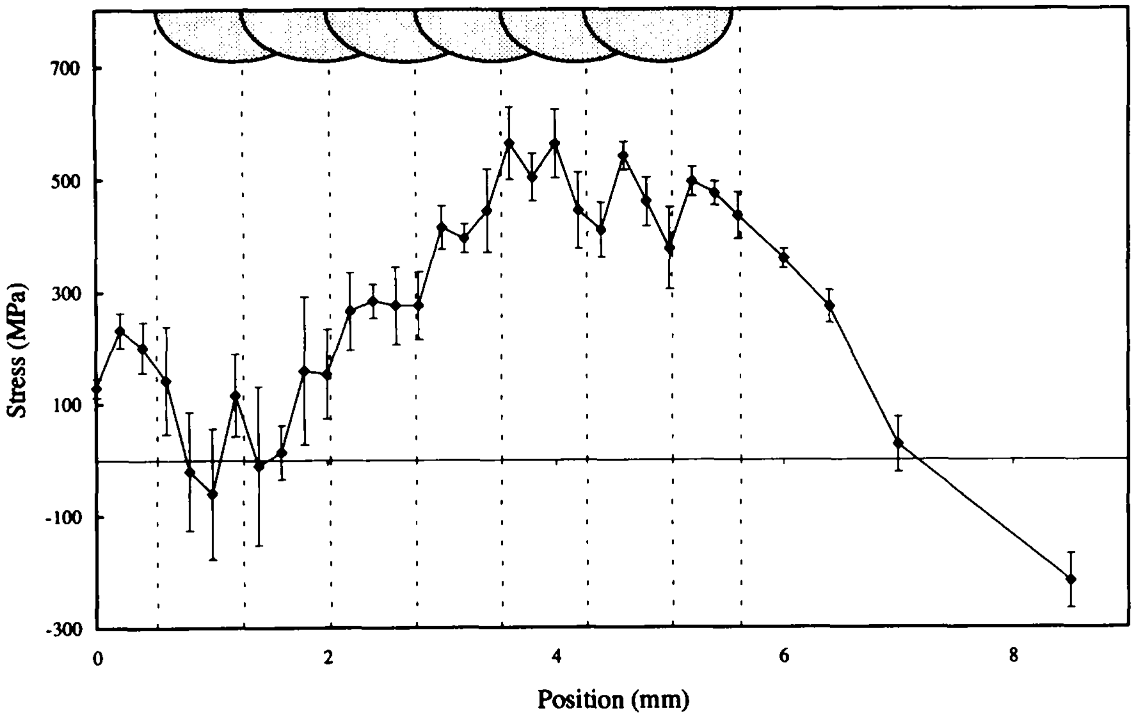


Fig. 2. The distribution of residual stress within six overlapping, adjacent laser melt tracks on Ti-6Al-4V substrate. The melt track cross-sections and their relative positions are illustrated schematically within the figure.

2.3. X-ray diffraction

X-ray data was gathered using a well aligned Philips X-ray diffraction system (PW 1830). The diffractometer was fitted with a fine-focus chromium tube operating at 40 kV and 35 mA. Initially, measurements were undertaken using a divergence slit of 1/30° but this was changed to 1/12° for the majority of measurements in order to increase counting statistics and thereby minimise error. A disadvantage of using a larger divergence slit is the associated decrease in the spatial resolution of the measurements. A divergence slit of 1/30° results in a beam width of 0.1 mm whereas 1/12° results in a beam width of 0.25 mm.

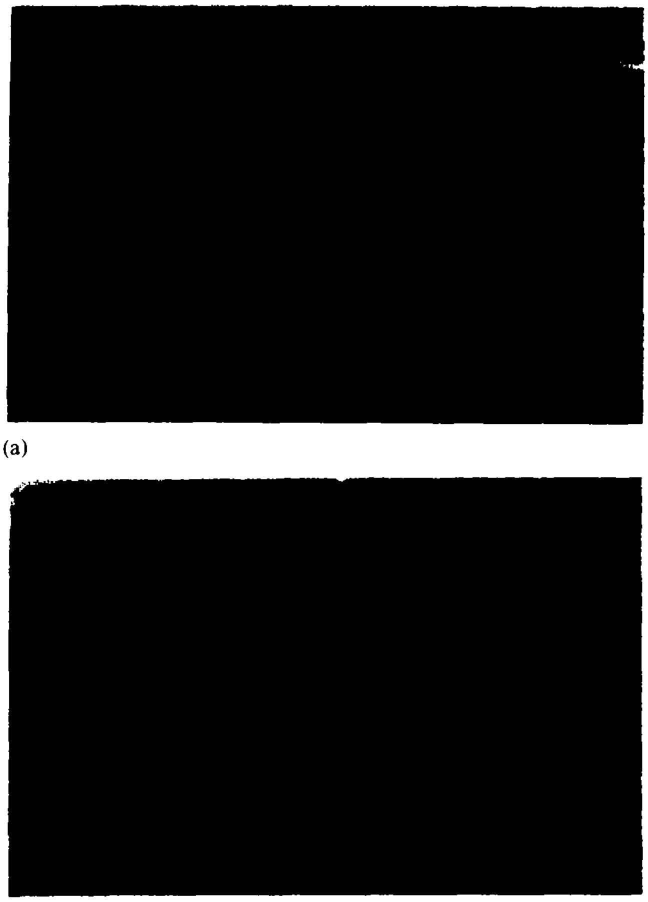
X-ray residual stress calculations were undertaken (using the $\sin^2 \Psi$ method [9]) at successive traversals of 0.2 mm perpendicular to the direction of the laser track. The use of a micrometer controlled traverse stage allowed for determination and resolution of the (transverse) residual stress distribution within the laser tracks. The technique is not described here in detail as the theoretical background and basic principles have been recently summarised [5].

3. Results and discussion

The residual stress state in the surface of the grit-blasted material prior to laser treatment was measured to be compressive (562 MPa). The severity of the grit-blasting is such that it results in substantial plastic deformation of the surface layers. The result suggests therefore that this is the maximum value of elastic stress that the material can withstand without some plastic accommodation of the stress. In this context, it is important to note a previous experimental result indicating that the residual stress state prior to laser melting has minimal influence on the final residual stress state within the laser track [5].

The distribution of residual stresses within and immediately outside a single melt track is shown in Fig. 1. The figure indicates that within the shallow surface layer of material penetrated by the X-rays there is a strong variation in the level of residual stress inside the melt track. The distribution of residual stresses is tensile within the centre of the track and compressive towards the edges. Moreover, immediately outside the melt-pool the stress in the heat affected zone is tensile. It can be expected that this will revert to compressive stress as the distance from the melt track increases. However, due to the time consuming nature of the technique, this detail was not measured.

The effect of overlapping adjacent melt tracks on the residual stress distribution is shown by the data plotted in Fig. 2. The data indicates a distribution of stress within the first melt track (left) which is approximately similar to that plotted in Fig. 1. However, it is immediately apparent from the figure that there is a progressive increase in the level of tensile residual stress as successive adjacent melt tracks are deposited. It is interesting to note that the maximum value of tensile stress (≈ 560 MPa) corresponds approximately with



(a)

(b)

Fig. 3. Scanning electron micrograph of the surface (a) and optical micrograph of the transverse cross-section (b) of laser nitrided Ti-6Al-4V substrate. The micrographs illustrate typical longitudinal crack formation associated with overlapping adjacent melt tracks.

the compressive stress level measured in the gritblasted surface prior to laser melting.

Dye penetrant examination of individual laser melt tracks within the course of the present work has illustrated and confirmed a number of important points. Under a particularly broad range of processing parameters (traverse velocity, power, power distribution) cracking was never detected when Ti-6Al-4V was laser melted in an inert environment. However, the introduction of nitrogen into the melt pool may or may not produce detectable cracking depending critically on the process parameters (including alloy gas dilution). When cracking does occur however, it is in the form of transverse cracks i.e. perpendicular to the direction of laser traverse. These results broadly confirm what has previously been reported in the literature e.g. [7,10].

In the case of overlapping adjacent melt-tracks, which are essential to the engineering application of the laser nitriding technique, longitudinal cracks i.e. parallel to the direction of laser traverse are detected under specific processing conditions [6]. Perhaps unsurprising is that the longitudinal cracks occur in multiple overlapping track samples using process parameters which had previously resulted in transverse cracks in the single track samples. More importantly, we have observed that even when no transverse cracking occurs in single track samples, multiple track samples may develop cracking. It is this observation which the X-ray residual stress measurement data presented in this work are able to explain. Typical examples of such longitudinal crack formation are illustrated in Fig. 3.

4. Summary and conclusions

X-ray residual stress measurements have been undertaken on laser surface melted samples of Ti-6Al-4V substrate. The data indicates a variation in the value of residual stress within a single melt track. Multiple overlapping adjacent melt tracks result in an increase in the measured value of the transverse residual stress, until the value saturates at approximately four times the tensile stress measured in a single track. This data can be used to rationalise the observation that cracking may occur in multi-track specimens, even when no cracks are detected in single-track samples produced under identical conditions. Moreover, the result emphasises the importance of extending experimental matrices beyond single-track experiments if the process data are to be applicable to the proposed engineering applications.

Acknowledgements

Primary financial support for the work of JMR and RCR from the Engineering and Physical Sciences Research Council (UK) under grant ref. GR/H 36535 is acknowledged. The work of BAV and JTMD is part of the research programme of the Foundation for Fundamental Research on Matter (Utrecht) and has been made possible by financial support from the Netherlands Organisation for Scientific Research (The Hague). The principal support for the collaboration in the form of a travel and subsistence grant for JMR was provided by the Netherlands Organisation for Scientific Research (NWO) and the British Council under the UK-Dutch joint scientific research project scheme.

References

[1] T. Bell, H.W. Bergmann, J. Lanagan, P.H. Morton and A.M. Staines, *Surface Engineering, 2* (1986) 133.

[2] T. Bell, P.H. Morton and B.L. Mordike, in R.W. Cahn (ed.), *Encyclopedia of Materials Science and Engineering*, Supp. Vol. 3, Pergamon, Oxford, 1993, pp. 2083-2087.

[3] B.L. Mordike in C.W. Draper and P. Mazzoldi (eds), *Laser Surface Treatment of Metals*, NATO Advanced Science Institute Series, Martinus Nijnhoff, Dordrecht, 1986, pp. 389-412.

[4] P.H. Morton, T. Bell, A. Weisheit, J. Kroll, B.L. Mordike and K. Sagoo, in T.S. Sudarshan and J.F. Braza (eds), *Surface Modification Technologies*, *5*, (1992) 593.
[5] B.A. Van Brussel and J. Th. M. De Hosson, *Mater. Sci. Eng.*, *A161* (1993) 83.
[6] J.M. Robinson, S. Anderson, R.D. Knutsen and R.C. Reed, *Mater. Sci. Tech.*, *11* (1995), 611.
[7] S. Mridha and T.N. Baker, *Mater. Sci. Eng.*, *A188* (1994) 229.
[8] E. Beyer, G. Herziger, R. Kramer and P. Loosen, *SPIE J. 650* (High Power Lasers and their Industrial Applications) (1986), 170.
[9] M.R. James and J.B. Cohen, in H. Herman (ed.), *Experimental Methods in Materials Science*, Vol. 1, Academic Press, New York, 1958.
[10] A.B. Kloosterman and J. Th. M. De Hosson, *Scr. Metall. 33*, (1995) 567.